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Resolving the era of river-forming climates on Mars using stratigraphic logs of river-deposit dimensions

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ABSTRACT

River deposits are one of the main lines of evidence that tell us that Mars once had a climate different from today, and so changes in river deposits with time tell us something about how Mars climate changed with time. In this study, we focus in on one sedimentary basin – Aeolis Dorsa – which contains an exceptionally high number of exceptionally well-preserved river deposits that appear to have formed over an interval of >0.5 Myr. We use changes in the river deposits' scale with stratigraphic elevation as a proxy for changes in river paleodischarge. Meander wavelengths tighten upwards and channel widths narrow upwards, and there is some evidence for a return to wide large-wavelength channels higher in the stratigraphy. Meander wavelength and channel width covary with stratigraphic elevation. The factor of 1.5–2 variations in paleochannel dimensions with stratigraphic elevation correspond to ∼2.6-fold variability in bank-forming discharge (using standard wavelength-discharge scalings and width-discharge scalings). Taken together with evidence from a marker bed for discharge variability at ∼10 m stratigraphic distances, the variation in the scale of river deposits indicates that bank-forming discharge varied at both 10 m stratigraphic (10^2–10^6 yr) and ∼100 m stratigraphic (10^3–10^9 yr) scales. Because these variations are correlated across the basin, they record a change in basin-scale forcing, rather than smaller-scale internal feedbacks. Changing sediment input leading to a change in characteristic slopes and/or drainage area could be responsible, and another possibility is changing climate (±50 W/m^2 in peak energy available for snow/ice melt).

1. Introduction

Many of the now-dry rivers on Mars were once fed by rain or by snow/ice melt, but physical models for producing that runoff vary widely (Malin et al., 2010; Mangold et al., 2004; Irwin et al., 2005a). Possible environmental scenarios range from intermittent <10^2 yr-duration volcanic- or impact-triggered transients to >10^6 yr duration humid greenhouse climates (Andrews-Hanna and Lewis, 2011; Kite et al., 2013a, 2014; Mischna et al., 2013; Segura et al., 2013; Urata and Toon, 2013; Tian et al., 2010; Halevy and Head, 2014; Wordsworth et al., 2013; Ramirez et al., 2014). These diverse possibilities have very different implications for the duration, spatial patchiness, and intermittency of the wettest (and presumably most habitable) past climates on Mars. As a set, these models represent an embarrassment of riches for the Mars research community, and paleo-environmental proxies (ideally, time series) are sorely needed to discriminate between the models. In principle, discriminating between the models using the fluvial record should be possible, because runoff intensity, duration and especially intermittency control sediment transport (e.g. Devauchelle et al., 2012; Morgan et al., 2014; Williams and Weitz, 2014; Erkeling et al., 2012; Kereszturi, 2014; Kleinhans et al., 2010; Kleinhans, 2005; Lamb et al., 2008; Hauber et al., 2009; Jaumann et al., 2005; Williams et al., 2011; Leeder et al., 1998; Barnhart et al., 2009; Howard, 2007). For example, Barnhart et al. (2009) and Hoke et al. (2011) both use geomorphic evidence for prolonged

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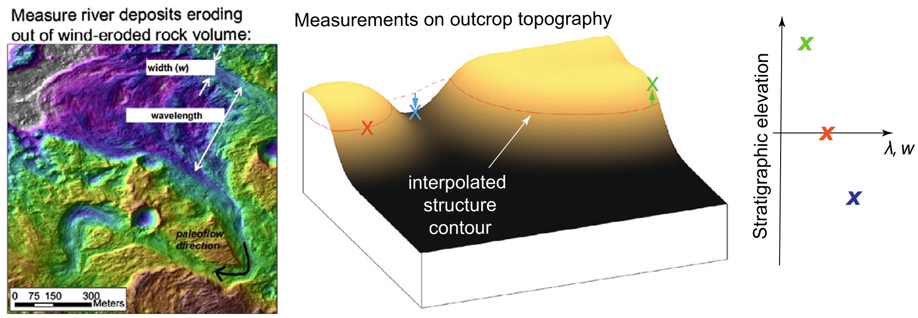

Fig. 1. Graphical abstract of this study. We measure the width (w) and wavelength (λ) of Mars river-deposits eroding out of the rock, assign stratigraphic elevations z_s to each measurement, and convert these to estimates of paleo-discharge $Q(z_s)$. Depth of chute cutoff (in left panel) is 2 m.

sediment transport to argue forcefully that impact-generated hypotheses for Early Mars runoff cannot be sustained.

However, geomorphology usually provides time-integrated runoff constraints, whereas constraining climate change requires time-resolved constraints; few locations on Mars show evidence for more than one river-forming episode; and correlation between those locations has to rely on crater counting, which (for this application) suffers from small-number statistics, cryptic resurfacing, target strength effects, confusion between primary and secondary craters, and inter-analyst variability (e.g. Dundas et al., 2010; Smith et al., 2008; Warner et al., 2014; Robbins et al., 2014). These problems have limited the application of dry-river evidence to constrain climate change during the era of river-forming climates on Mars.

Aeolis Dorsa (1°S–8°S, 149°E–156°E) – a wind-exhumed sedimentary basin 10°E of Gale crater that contains an exceptionally high number of exceptionally well-preserved river deposits – gets around these problems. At Aeolis Dorsa, basin-scale mapping distinguishes 10^2 m-thick river-deposit-hosting units, which collectively provide time-resolved climate constraints (river valleys provide time-integrated constraints) (Kite et al., 2015). We can put these deposits in time order using crosscutting relationships, which lack the ambiguity of crater counts. Paleodischarge can be estimated from meander wavelengths and channel widths (Burr et al., 2010). Therefore, Aeolis Dorsa contains a stratigraphic record of climate-driven surface runoff on Mars (Burr et al., 2010; Fairén et al., 2013; Kite et al., 2015).

To constrain paleodischarge versus time, in this study we measure how river-deposit dimensions vary with stratigraphic elevation (Hajek and Wolinsky, 2012). The key results are set out in Table 1. We review terrestrial background and geologic context in Section 1.1. We introduce our method (Fig. 1) in Section 2; this method is generally applicable to stratigraphic logging from stereopairs (not just logs of river-deposit dimensions). We report our dataset, describe our paleodischarge interpretation, and discuss the implications for fluvial intermittency and abrupt climate change in Section 3. We discuss implications for paleodischarge variability in Section 4, assess the science merit of landing at Aeolis Dorsa in Section 5, and conclude in Section 6.

1.1. *Fluvial signatures of climate events on Mars: clearer than Earth*

Fluvial sediments record climate events in Earth history through changes in river-deposit dimensions, channel-deposit proportions, and fluvial styles (e.g. Foreman et al., 2012; Macklin et al., 2012; Amundson et al., 2012; Schmitz and Pujalte, 2007).

Dry rivers are most useful in reconstructing climate change when the record is preserved as deposits (as at Aeolis Dorsa) and when it is uncontaminated by large-amplitude externally-driven tectonic uplift (as at Aeolis Dorsa). Mars lacks plate tectonics and

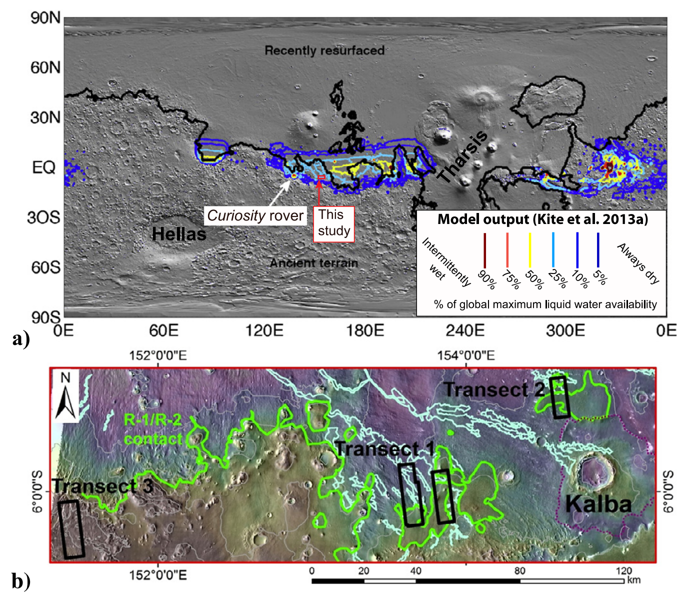

Fig. 2. a) Locator map for our study area (red rectangle). Background is shaded relief Mars Orbiter Laser Altimeter (MOLA) topography, illuminated from top right. Colored contours show output from a seasonal melting model (Kite et al., 2013a: relative frequency of years with seasonal surface liquid water, average of 88 different orbitally-integrated thin-atmosphere simulations). The black line marks the border of the area of recently-resurfaced terrain, and approximately corresponds to the hemispheric dichotomy. This figure is modified from Fig. 16d in Kite et al. (2013a). b) Zooming in to our study area, showing locations of transects (black rectangles; detail shown in Supplementary Materials Section A2). Transect 1 consists of two nearby non-contiguous areas. Green line shows trace of R-1/R-2 contact ($z_s = 0$ m). R-2 is above the contact (orange/red tints), and R-1 is below the contact (purple/blue tints). Grey contours are MOLA topography, at 200 m intervals. Background colors correspond to the elevation from MOLA (blue is low and red is high). Cyan outlines correspond to large meander belts, which disappear beneath and reappear from underneath smooth dome-shaped outcrops of R-2. Purple dashed line outlines an old crater. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

has been tectonically quiescent for >3 Ga (Golombek and Phillips, 2012), making the fluvial record of climate change clearer than on Earth where the strong effects of base-level fluctuations and synfluvial tectonics complicate interpretation of the fluvial record in terms of climate change (e.g. Blum and Törnqvist, 2000). Reviewing Earth work, Whittaker (2012) states "If topography forms a non-unique or difficult-to-decode record of past climate [...], it is likely that the sedimentary record, if and where complete, forms the best archive of landscape response to past climate."

The sedimentary record in Aeolis Dorsa is >3 km thick (Kite et al., 2015), and this study focuses on ∼300 m of stratigraphy bracketing the contact (green line in Fig. 2b) between two river-deposit-containing units that show dramatically different erosional